

News from CTEQ-TEA PDF analysis

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in collaboration with
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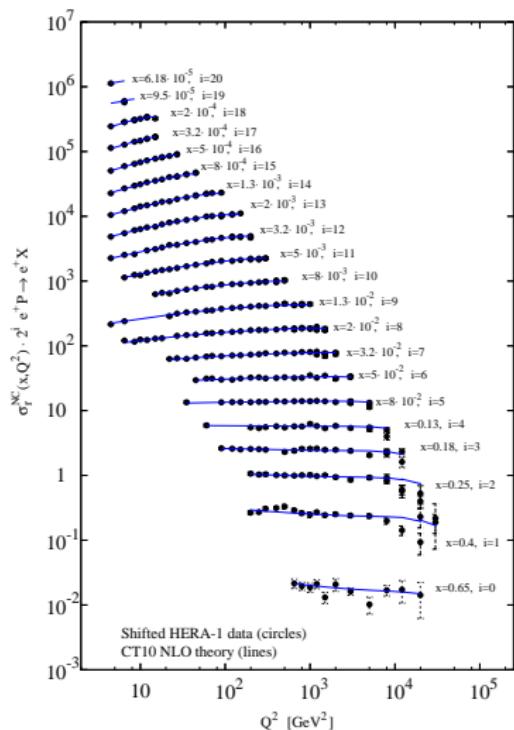
April 11, 2010

CTEQ-Tung Et Al.: ongoing activities

- CT10 and CT10W general-purpose NLO PDF sets
- NNLO CTEQ global analysis (in progress)
 - ▶ Validation of $O(\alpha_s^2)$ heavy-quark contributions to DIS is completed (**details by M. Guzzi** in the HQ WG session)
- Effects of new experimental data on PDFs
 - ▶ W lepton asymmetry, F_2^n/F_2^p , comparisons with the LHC data
 - ▶ dependence on the PDF parametrization form (**J. Pumplin**, today)
- DGLAP factorization in DIS at small x

CT10 parton distribution functions (PRD82, 074024 (2010))

- General-purpose NLO PDFs
- Adequate for the majority of PQCD applications
- combined HERA-1 data are included
- detailed analysis of the Tevatron Run-2 W asymmetry (A_ℓ) data
 - ▶ CT10 and CT10W sets, with different treatment of A_ℓ
- last PDF analysis without the LHC data

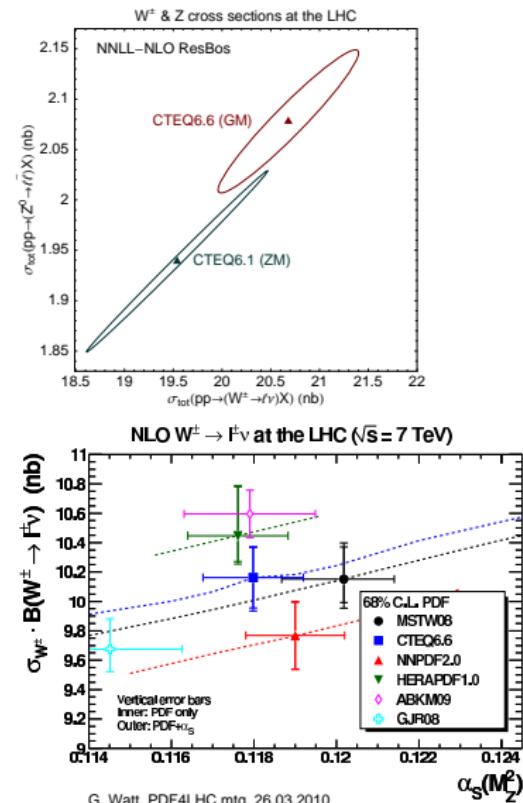


CT10 parton distribution functions (PRD82, 074024 (2010))

- 53 CT10/CT10W eigenvector sets for $\alpha_s(M_Z) = 0.118$
 - ▶ 4 CT10AS/CT10WAS PDFs for $\alpha_s(M_Z) = 0.116 - 0.120$
 - ◊ The correlated PDF+ α_s uncertainty on an observable X is computed by
$$\Delta X_{PDF+\alpha_s} = \sqrt{\Delta X_{PDF, CT10}^2 + \Delta X_{\alpha_s, CT10AS}^2},$$
as explained in PRD 82,054021 (2010)
 - ▶ CT10/CT10W PDFs with 3 and 4 active flavors
 - In the LHADPF library and at <http://hep.pa.msu.edu/cteq/public/index.html>

NNLO global PDF analysis

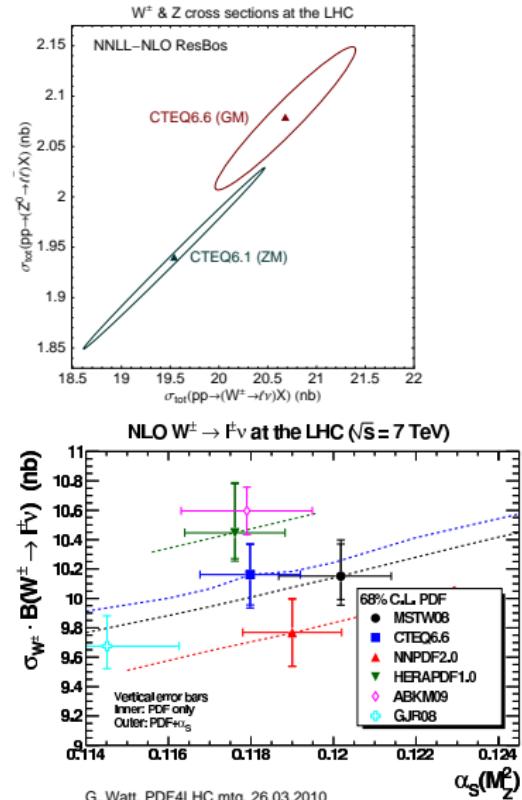
- Time is ripe for producing NNLO PDFs
- Accuracy of many EW, DIS, jet data becomes comparable to NNLO contributions
- Heavy-quark mass effects in DIS at $Q \approx m_Q$ is the key challenge for NNLO global fits
 - ⇒ 5-7% differences in $\sigma_{W,Z}$ at the LHC (*Tung et al., hep-ph/0611254*)
- For comparison, NNLO hard-scattering correction to $\sigma_{W,Z}$ is $\approx 2\%$



G. Watt, PDF4LHC mtg, 26.03.2010

NNLO global PDF analysis

NNLO DIS contributions are fully implemented in the S-ACOT scheme, the default factorization scheme of CTEQ6.6 and CT10 PDFs



G. Watt, PDF4LHC mtg, 26.03.2010

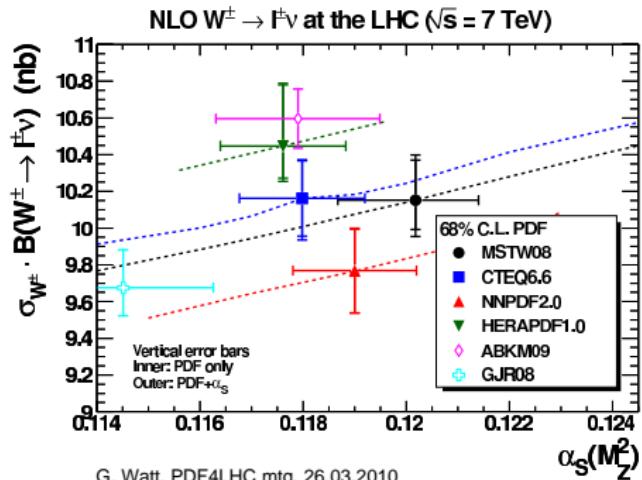
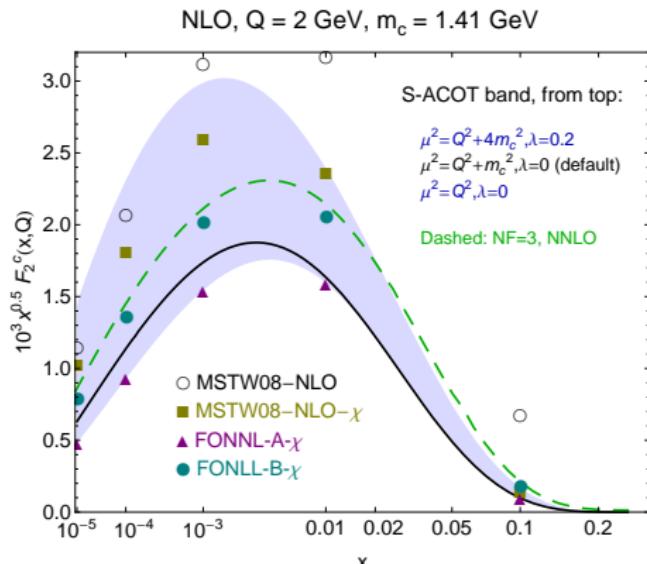
Simplified Aivazis-Collins-Olness-Tung scheme

ACOT, PRD 50 3102 (1994); Collins, PRD 58 (1998) 094002; Kramer, Olness, Soper, PRD (2000) 096007

- Derivation is based upon, and closely follows, the proof of QCD factorization for DIS with massive quarks (*Collins, 1998*)
- Relatively simple
 - ▶ One value of N_f (and one PDF set) in each Q range
 - ▶ Straightforward matching based on kinematical rescaling
 - ▶ Sets $m_Q = 0$ in ME with incoming c or b
- Reduces to the ZM \overline{MS} scheme at $Q^2 \gg m_Q^2$, without additional renormalization
- Reduces to the FFN scheme at $Q^2 \approx m_Q^2$
 - ▶ has reduced dependence on tunable parameters at NNLO

Input parameters of the S-ACOT scheme

At NLO, the charm mass m_c , factorization scale μ , and rescaling variable ζ of CTEQ PDFs are **tuned** to best describe the DIS data



2009 Les Houches HQ benchmarks
with toy PDFs; default $\mu = Q$

W, Z cross sections;
 $m_c = 1.3 \text{ GeV}$ in CTEQ6.6

NNLO results for $F_2^{(c)}(x, Q^2)$ - Preliminary

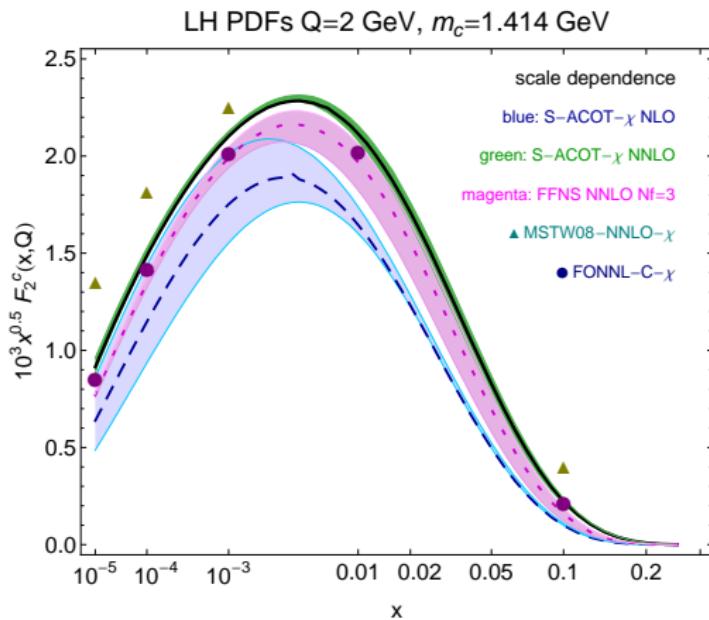
At NNLO and $Q \approx m_c$:

S-ACOT- χ ($N_f = 4$) \approx FFN ($N_f = 3$)
without tuning

■ S-ACOT is numerically close to other NNLO schemes

■ NNLO expressions are close to the FONLL-C scheme

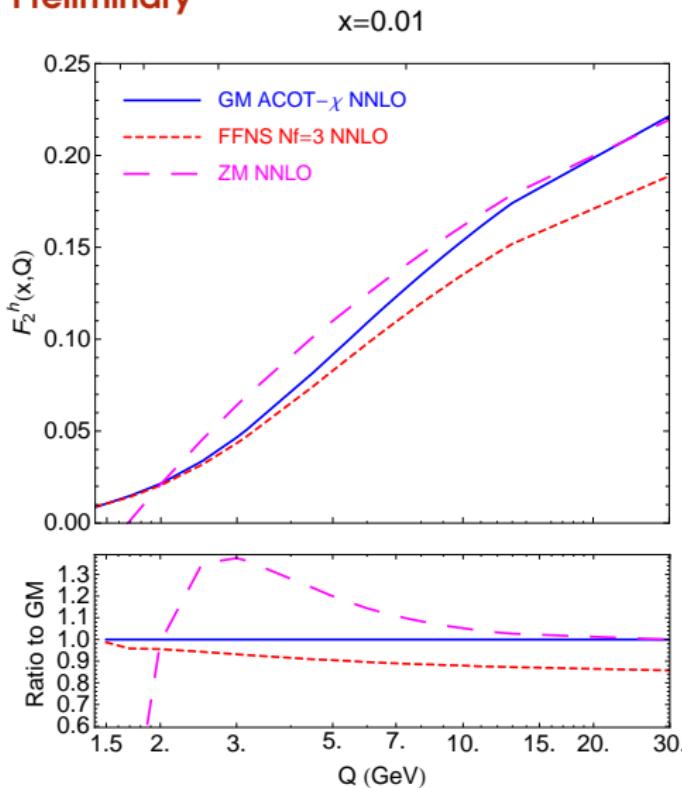
(Forte, Laenen, Nason, arXiv:1001.2312).



■ ACOT formalism provides recipe-like formulas for implementing NNLO in the GM scheme (\Rightarrow Guzzi)

New: $F_2^{(c)}(x, Q^2)$ in S-ACOT scheme at NNLO

Preliminary



NNLO calculation
for $F_{2,L}^c(x, Q)$ is
implemented in
the CTEQ fit
(Guzzi, Lai,

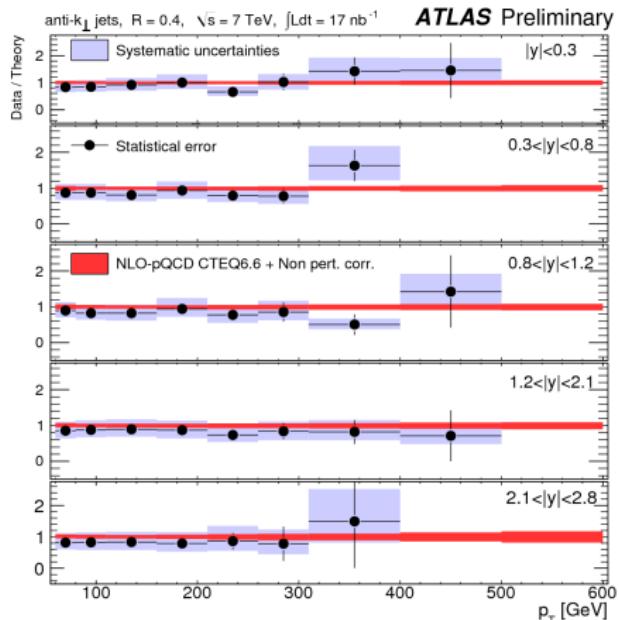
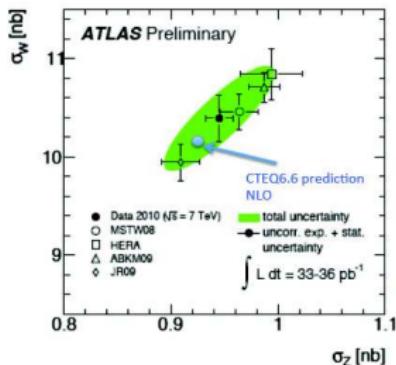
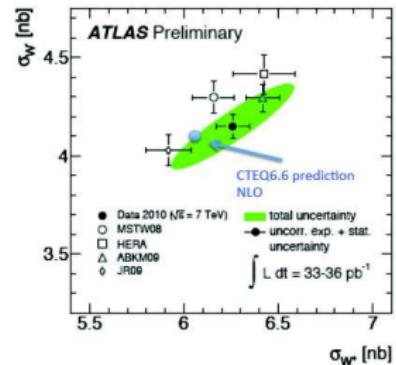
PN., Yuan, in preparation)

ACOT reduces
to FFNS at $Q \approx m_c$
and to ZM at $Q \gg m_c$

Les Houches toy
PDFs, evolved at
NNLO with
threshold matching
terms

CTEQ PDFs vs. the latest data: LHC

Agreement with many LHC measurements



+data on σ_W/σ_Z , $t\bar{t}$, $\gamma\gamma$, etc.

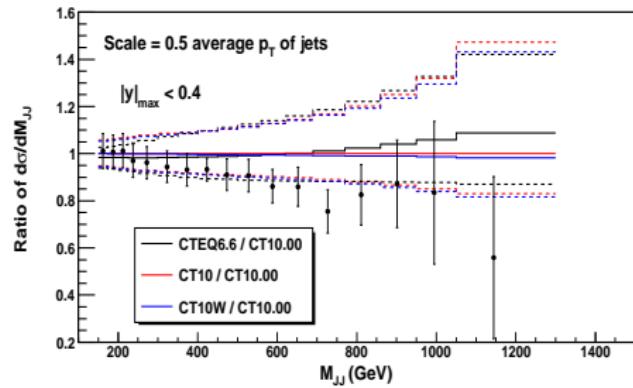
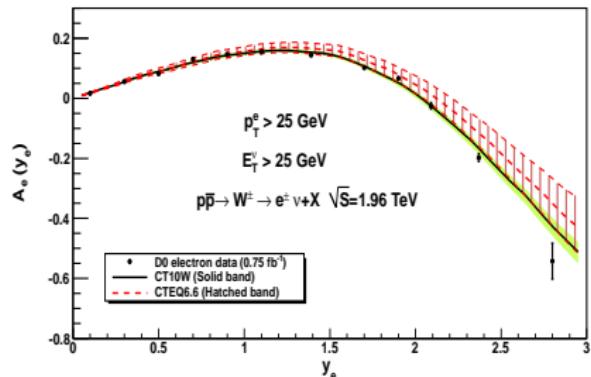
Figures are from ATLAS. Similar results from CMS

CTEQ PDFs vs. the latest data: Tevatron

Outstanding puzzles:

1. Run-2 W charge asymmetry
(constraining $d(x, Q)/u(x, Q)$
at $x > 0.1$)
2. Inclusive (di)jet production
(constraining $g(x, Q)$ at
 $x > 0.1$)

In both processes, experimental accuracy is high enough to start feeling effects beyond NLO and of resummations



The puzzle of the CDF/D0 W lepton asymmetry

- CT10W set reasonably agrees with 3 p_{Te} bins of $A_e(y_e)$ and one bin of $A_\mu(y_\mu)$ from D0 Run-2 (2008).
- NNPDF 2.0 ([arXiv:1012.0836](#)) agrees with $A_\mu(y_\mu)$, disagrees with two p_{Te} bins of $A_e(y_e)$.
- CT10, many other PDFs fail.

Agreement of PQCD with D0 $A_e(y_e)$	χ^2/npt	Source or comments
CTEQ6.6, NLO	$191/36=5.5$	<i>Our study;</i> <i>Resbos, NNLL-NLO</i>
CT10W, NLO	$78/36=2.2$ With $A_\mu(y_\mu)$: $88/47=1.9$	
ABKM'09, NNLO	$540/24=22.5$	<i>Catani, Ferrera, Grazzini,</i> <i>JHEP 05, 006 (2010)</i>
MSTW'08, NNLO	$205/24=8.6$	
JR09VF, NNLO	$113/24=4.7$	

Why difficulties with fitting $A_\ell(y_\ell)$?

1. $A_\ell(y_\ell)$ is very sensitive to the average slope s_{du} of $d(x, M_W)/u(x, M_W)$

$$A_\ell(y_\ell) \sim A_\ell(y_W)|_{LO} \propto \frac{1}{x_1 - x_2} \left[\frac{d(x_1)}{u(x_1)} - \frac{d(x_2)}{u(x_2)} \right]; \quad x_{1,2} = \frac{Q}{\sqrt{s}} e^{\pm y_W}$$

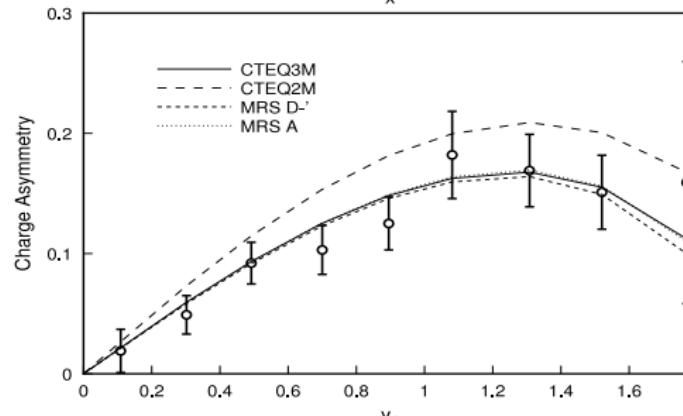
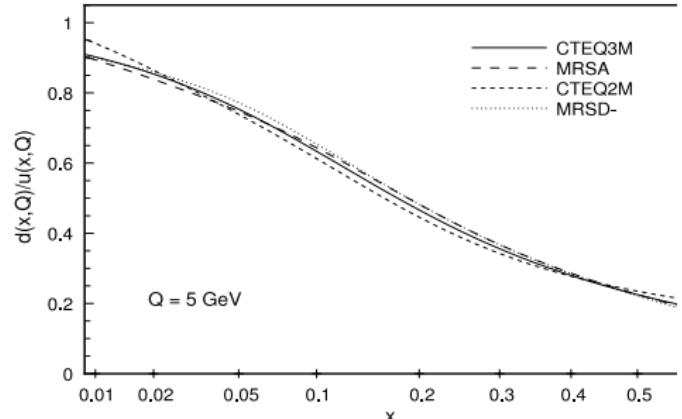
Berger, Halzen, Kim, Willenbrock, PRD 40, 83 (1989); Martin, Stirling, Roberts, MPLA 4, 1135 (1989); PRD D50, 6734 (1994); Lai et al., PRD 51, 4763 (1995)

2. Constraints on s_{du} by fixed-target $F_2^d(x, Q)/F_2^p(x, Q)$ are affected by nuclear and higher-twist effects

Accardi, Christy, Keppel, Monaghan, Melnitchouk, Morfin, Owens, PRD 81, 034016 (2010)

The agreement of CT10W with Tevatron A_ℓ introduces tension with NMC, BCDMS $F_2^{p,d}$ data

Challenges with fitting $A_\ell(y_\ell)$



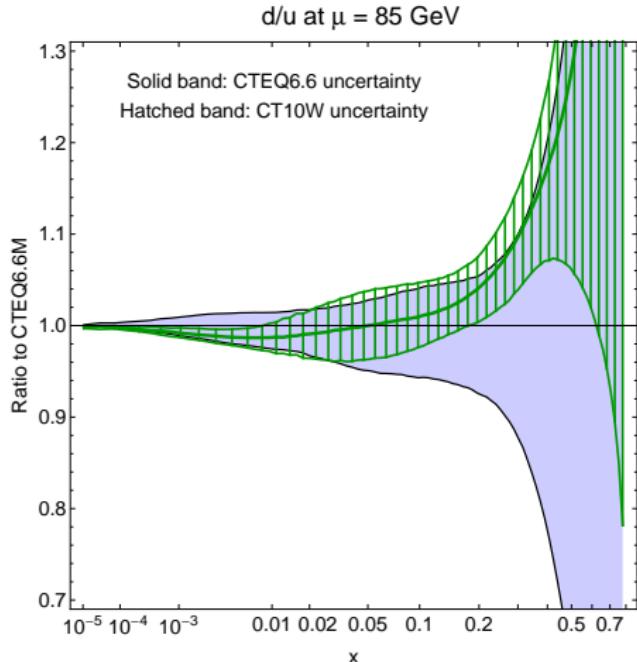
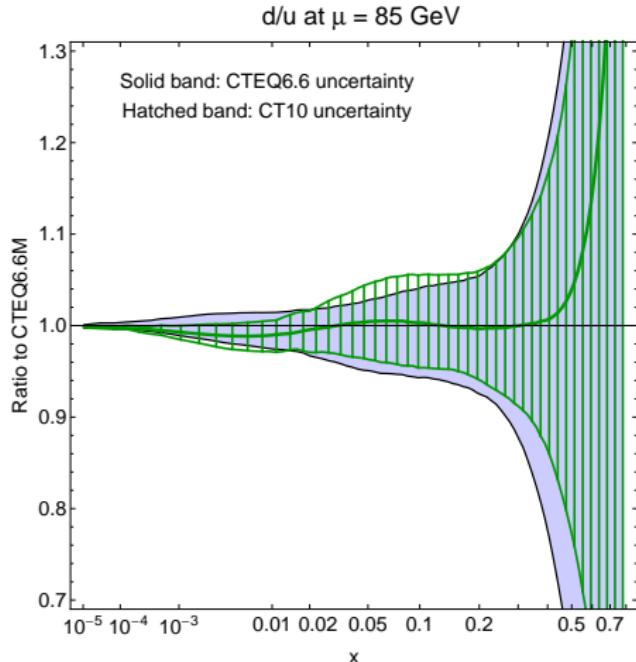
Small changes in s_{du} cause significant variations in A_ℓ

Lai *et al.*, PRD 51, 4763 (1995)

Alternative constraints on d/u by $F_2^d(x, Q)/F_2^p(x, Q)$ from fixed-target DIS are affected by nuclear and higher-twist effects

Accardi, Christy, Keppel, Monaghan, Melnitchouk, Morfin, Owens, PRD 81, 034016 (2010)

$d(x, Q)/u(x, Q)$ at $Q = 85$ GeV



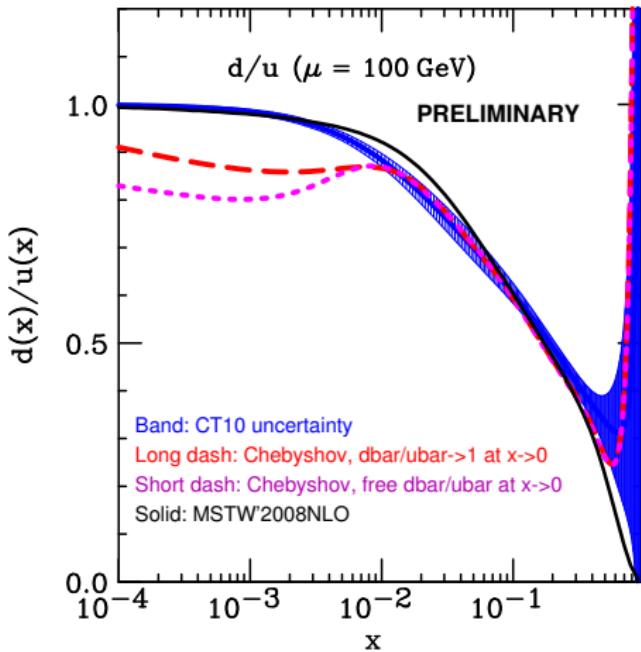
CT10W prefers a larger slope of d/u , has a smaller uncertainty than CTEQ6.6 or CT10

Why difficulties with fitting $A_\ell(y_\ell)$?

3. Existing parametrizations underestimate the PDF uncertainty on d/u

PDFs based on Chebyshov polynomials improve agreement with D0 Run-2 A_e , but are outside of current CTEQ/MSTW bands (*Pumplin*)

This ambiguity is reduced by $A_\ell(y_\ell)$ at the LHC, which constrains d/u and \bar{d}/\bar{u} at $x \sim 0.01$.



Why difficulties with fitting $A_\ell(y_\ell)$?

4. Experimental A_ℓ with lepton $p_{T\ell}$ cuts is sensitive to $d\sigma/dq_T$ of W boson at transverse momentum $q_T \rightarrow 0$.

- Fixed-order (N)NLO calculations (DYNNLO, FEWZ, MCFM,...) predict a wrong shape of $d\sigma/dq_T$ at $q_T \rightarrow 0$.
- Small- q_T resummation correctly predicts $d\sigma/dq_T$ in this limit.
- CT10(W) PDFs are fitted using a NNLL-NLO+K resummed prediction for A_ℓ (ResBos); **must not be used with fixed-order predictions for A_ℓ** .

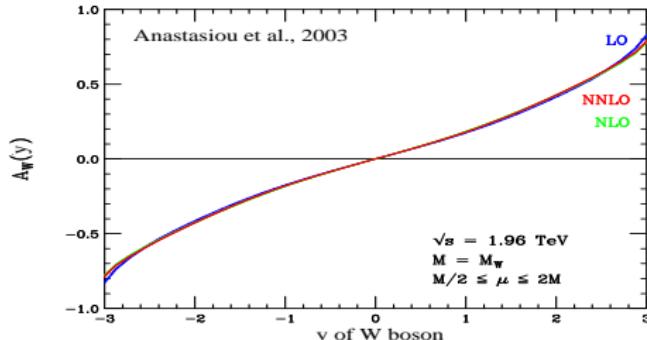
For example:

$$\chi^2(\text{CT10W+ResBos}) = 1.9 N_{pt \text{ (us)}};$$

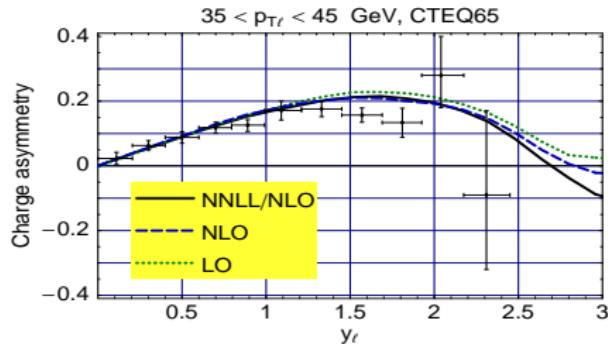
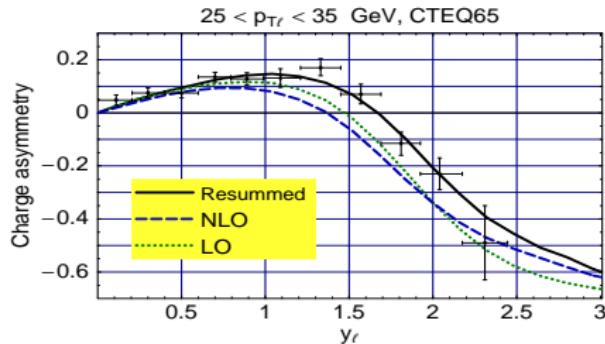
$$\chi^2(\text{CT10W+DYNLL}) = 8.4 N_{pt \text{ (NNPDF)}}$$

Charge asymmetry in p_T^e bins (CDF Run-2, 207 pb $^{-1}$)

Without the p_T^e cut (FEWZ):

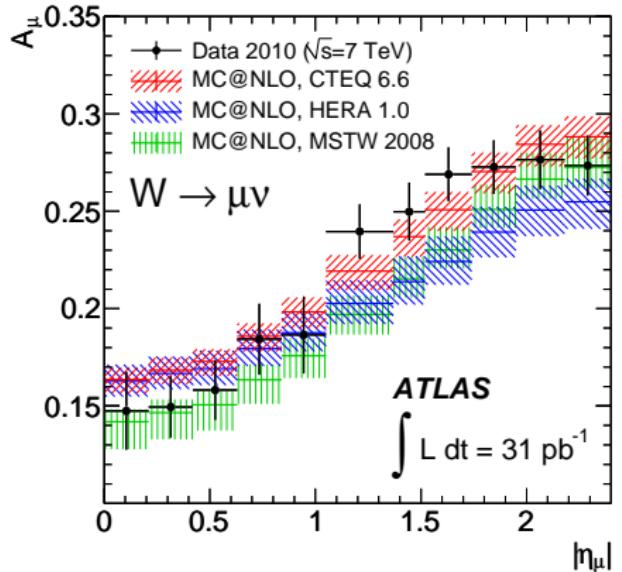


With p_{Te} cuts imposed, $A_{ch}(y_e)$ is sensitive to small- Q_T resummation

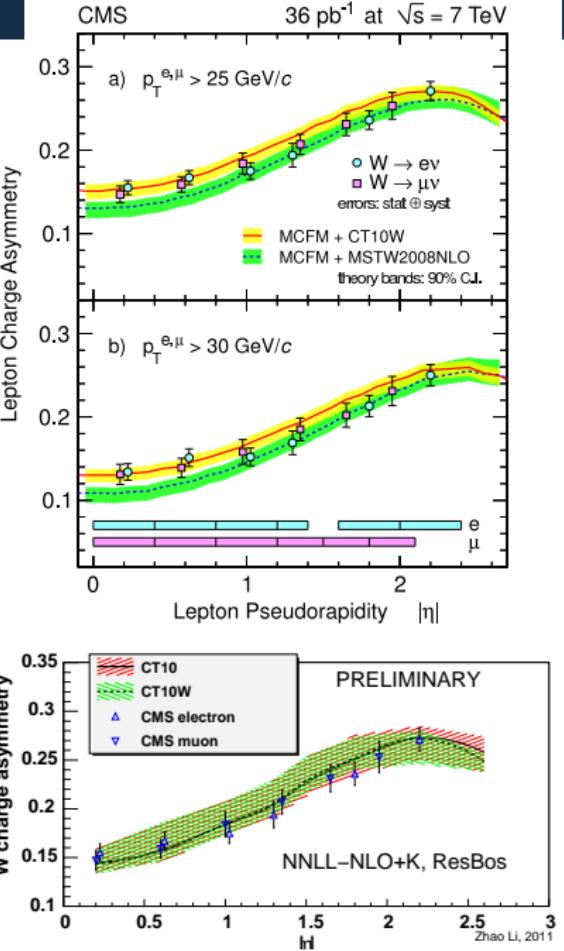


PN, 2007, unpublished; arXiv:1101.0561

CT10(W) vs. A_ℓ at the LHC

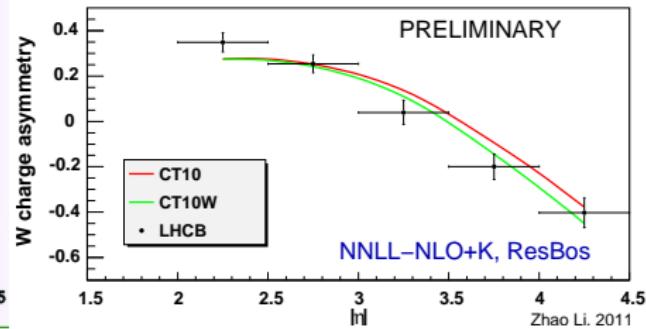
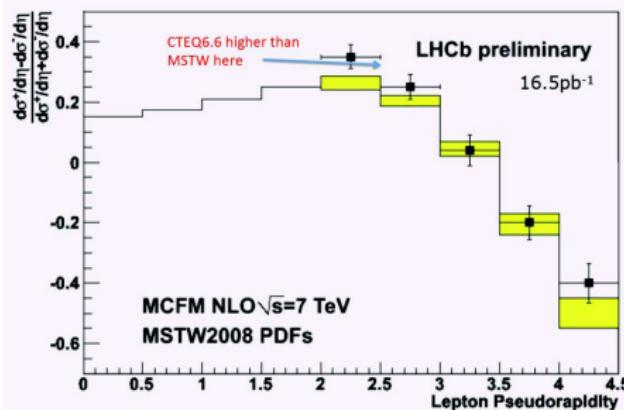


CT10(W) agrees well with the LHC A_ℓ ; some differences between NLO and NNLL+NLO



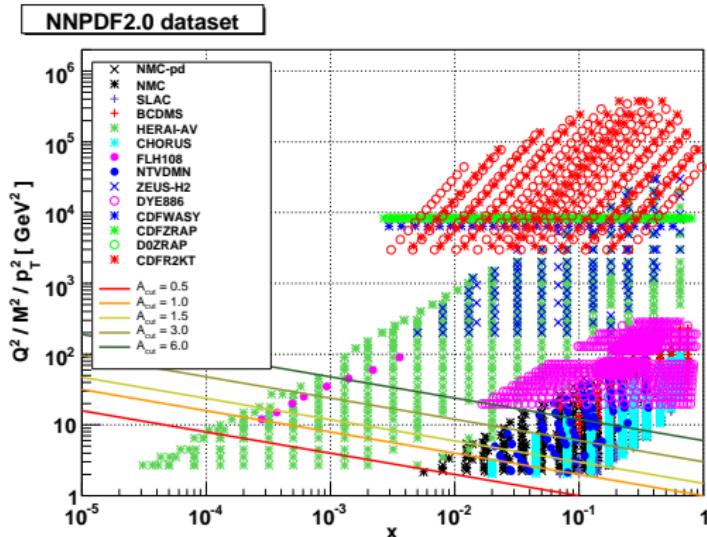
CT10(W) vs. A_ℓ : LHC-B

LHCb asymmetry measurement; from PDF4LHC Mar 7



LHC-B marginally prefers CT10W

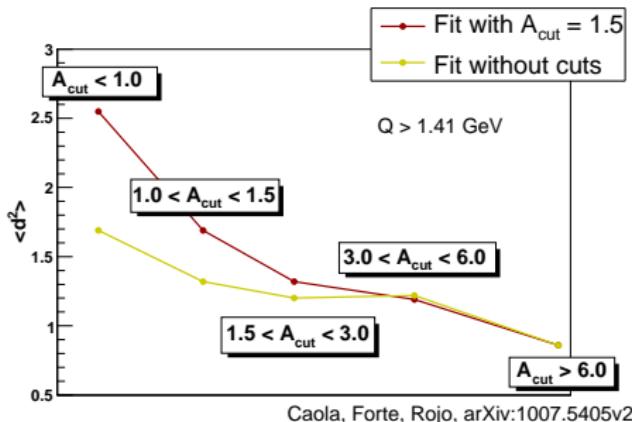
A_{cut} fits to combined HERA data



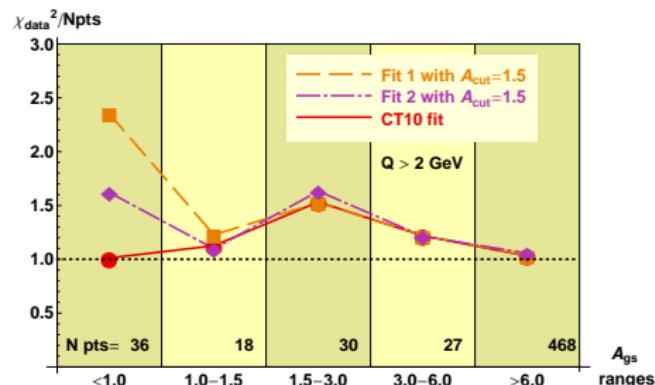
Fitting procedure:

- Include only DIS data above an A_{cut} line
- Compare the resulting PDFs with DIS data below the A_{cut} line, in a region that is “connected” by DGLAP evolution

CT10: A_{cut} fits to DIS data at $Q > Q_0 = 2$ GeV



Caola, Forte, Rojo, arXiv:1007.5405v2

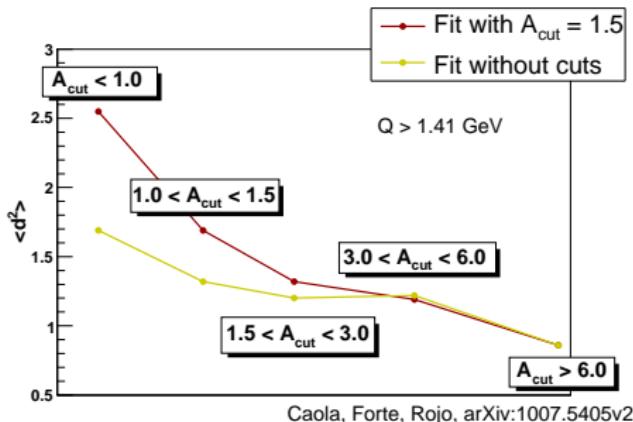


Motivation

Search for deviations from DGLAP evolution at smallest x and Q

- Follow the procedure proposed by NNPDF2.0 (arXiv:1007.5405)

CT10: A_{cut} fits to DIS data at $Q > Q_0 = 2$ GeV



Caola, Forte, Rojo, arXiv:1007.5405v2

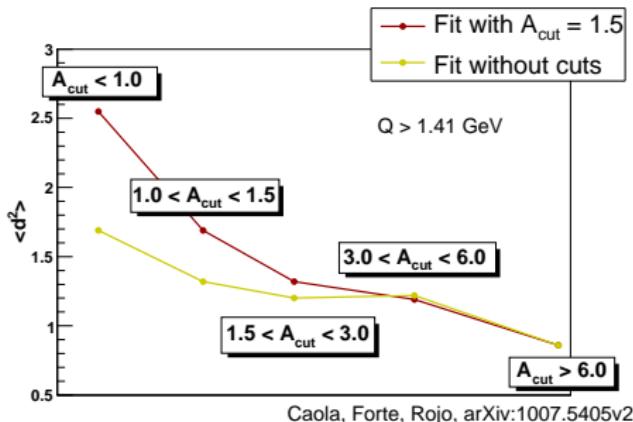
CT10

Two CT10-like fits to data at $A_{gs} > 1.5$, with different parametrizations of $g(x, Q)$

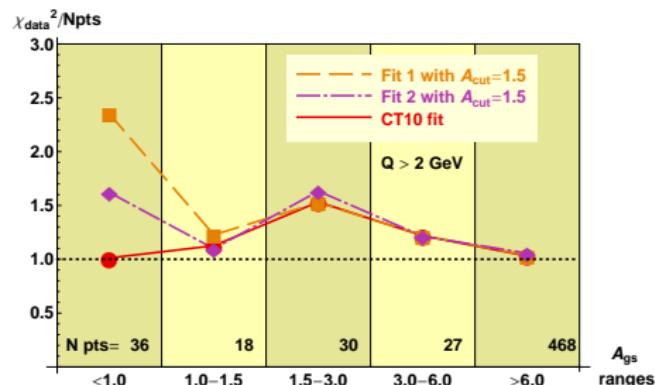
$$\chi_i^2 = \frac{(\text{Shifted Data} - \text{Theory})^2}{\sigma_{uncor}^2}$$

Large syst. shifts at $A_{gs} < 1.0$, in a pattern that could mimic a slower Q^2 evolution

CT10: A_{cut} fits to DIS data at $Q > Q_0 = 2$ GeV



Caola, Forte, Rojo, arXiv:1007.5405v2



CT10, cont.

$\delta\chi^2 \sim 0$ at $A_{gs} > 1.0$
(no difference)

$\delta\chi^2 = 0 - 1.5$ at $A_{gs} < 1.0$,
with large uncertainty

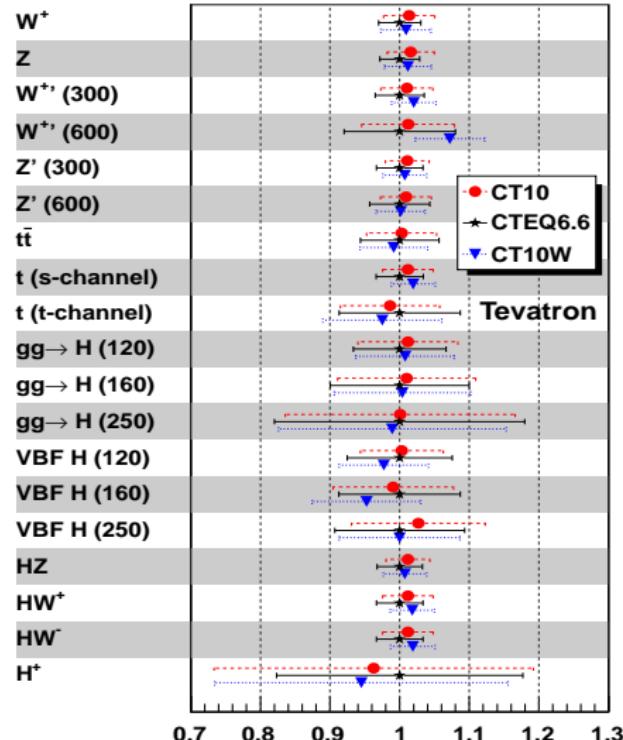
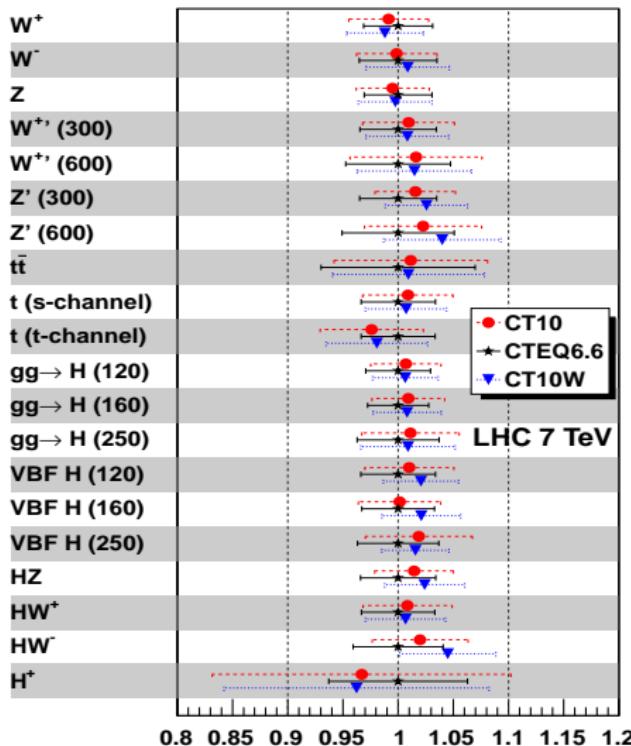
⇒ Disagreement with the “DGLAP-connected” data at $A_{gs} < A_{cut}$ is not supported by the CT10 fit

Conclusions

- In the CTEQ-TEA fit, an NNLO calculation for $F_{2,L}^{c,b}$ in the S-ACOT scheme is demonstrated to be viable.
- This is the most challenging component of the NNLO CTEQ PDF analysis, to be made available soon.
- Progress in understanding of new Tevatron and LHC data sets, PDF parametrization issues
- **arXiv:1101.0561:** synopsis of recent CTEQ-TEA publications
 - ▶ CT10W fit to Run-2 W charge asymmetry; PDFs for leading-order showering programs; constraints on color-octet fermions

CT10 & CT10W predictions for the near future

Total cross sections



Backup slides

S-ACOT input parameters

At $Q \approx m_c$, F_2^c depends significantly on

- 1. Charm mass:** $m_c = 1.3$ GeV in CT10
- 2. Factorization scale:** $\mu = \sqrt{Q^2 + \kappa m_c^2}$; $\kappa = 1$ in CT10
- 3. Rescaling variable** $\zeta(\lambda)$ for matching in $\gamma^* c$ channels

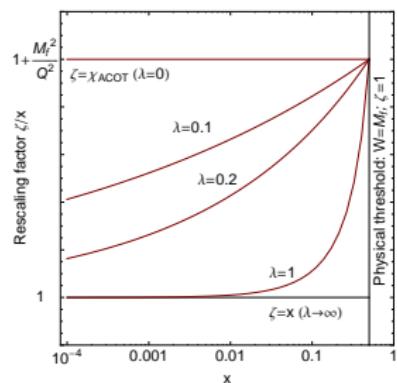
(Tung et al., hep-ph/0110247; Nadolsky, Tung, PRD79, 113014 (2009))

$$F_i(x, Q^2) = \sum_{a,b} \int_{\zeta}^1 \frac{d\xi}{\xi} f_a(\xi, \mu) C_{b,\lambda}^a \left(\frac{\zeta}{\xi}, \frac{Q}{\mu}, \frac{m_i}{\mu} \right)$$

$$x = \zeta / \left(1 + \zeta^\lambda \cdot (4m_c^2)/Q^2 \right), \text{ with } 0 \leq \lambda \lesssim 1$$

CT10 uses

$$\zeta(0) \equiv \chi \equiv x \left(1 + 4m_c^2/Q^2 \right),$$

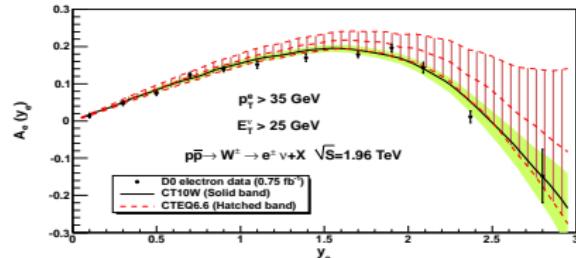
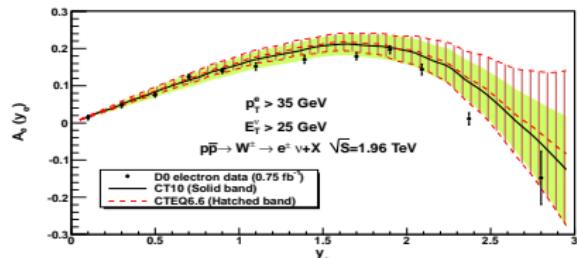
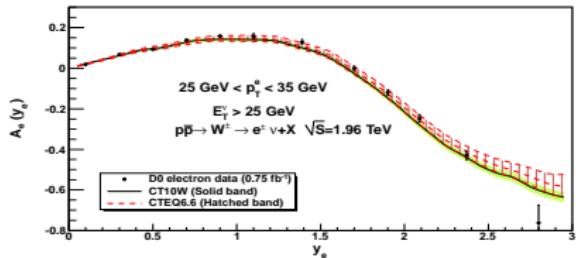
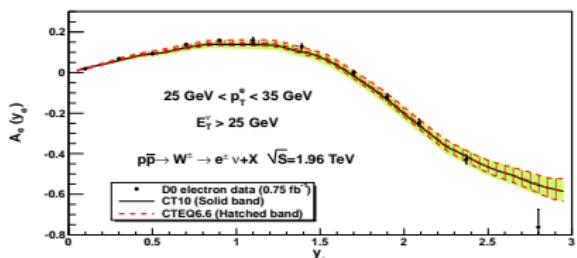
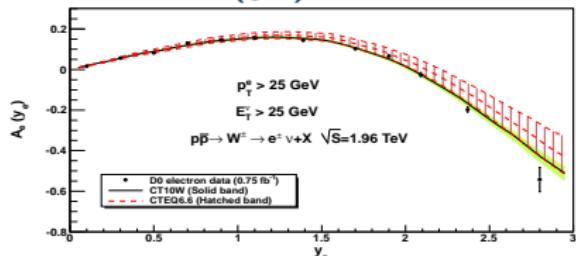
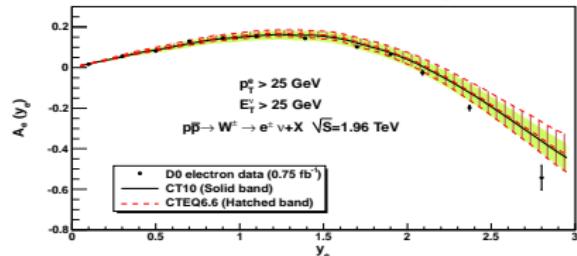


motivated by momentum conservation

CT10(W): radiative contributions to $A_\ell(y_\ell)$

- **Default calculation:** $A_\ell(y)$ at NNLL-NLO, using lookup tables for $\sigma(p_T^\ell, y_\ell)_{NNLL+NLO}/\sigma(p_T^\ell, y_\ell)_{LO}$ from ResBos (*Balazs, Yuan, PRD 56, 5558 (1997); Landry, Brock, P.N. Yuan, PRD67, 073016 (2003)*).
- **Cross check:** include NNLO corrections at $Q_T \approx M_W$ (*Arnold & Reno, 1989*); $A_\ell(y_\ell)$ changes by a few percent at the highest y_ℓ and $p_T > 35$ GeV
 - ▶ magnitude of changes is comparable with full NNLO terms (*Catani, Ferrera, and Grazzini, JHEP 05, 006 (2010)*)
 - ▶ changes are small compared to the experimental errors

CT10 and CT10W predictions for $A_e(y_e)$ (D0 Run-2)

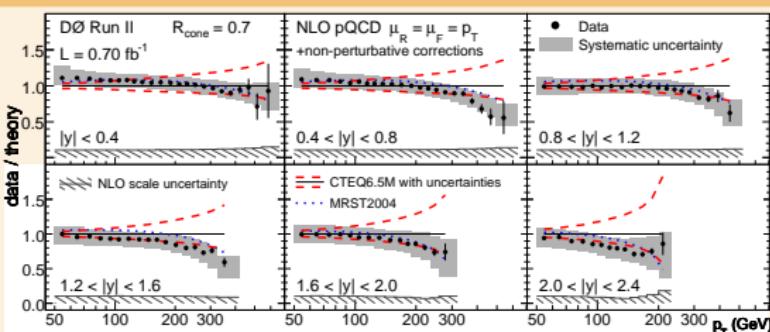


Do CTEQ PDFs disagree with D0 (di)-jet data?

Pumplin et al., PRD 80 (2009) 014019: discrepancy between CTEQ6.6/09/10 PDFs and Tevatron incl. jet data is exaggerated

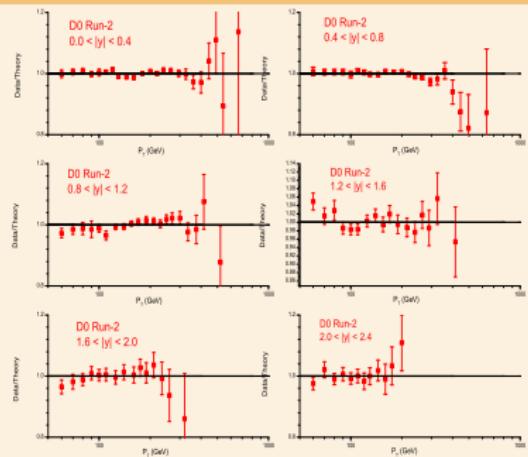
Same data and theory, plotted by D0 (left) and CT09 analysis (right)

D0 Coll., arXiv:0802.2400 (700 pb⁻¹)



“Disagreement”

(Shifted D0-Run 2 data)/CT09



Excellent agreement

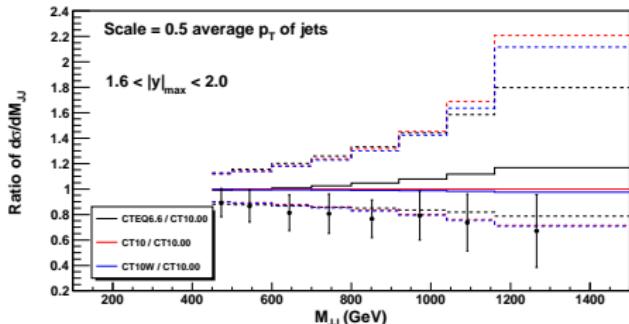
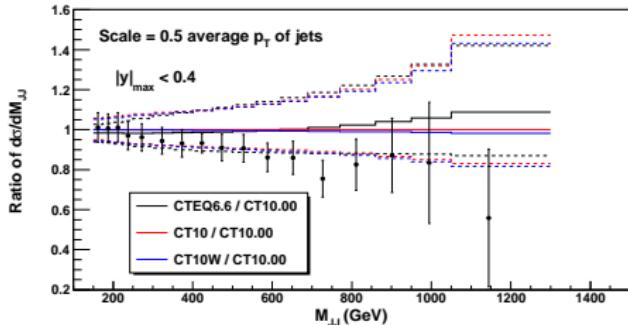
Jet production: issues to consider

- Significant scale dependence

- ▶ Comparisons of CT10 PDFs to (di)jet data must use $\mu = p_T^{jet}/2$, the same scale as in the CT10 fit

- Differences between NLO codes; sensitivity to resummation of jet differential distributions
(Alioli et al., arXiv:1012.3380)

- In the CT09 fit, correlated systematic shifts reconcile the data with a wider range of PDFs than in the standalone experimental analysis



Resummation effects in inclusive (di)jet production

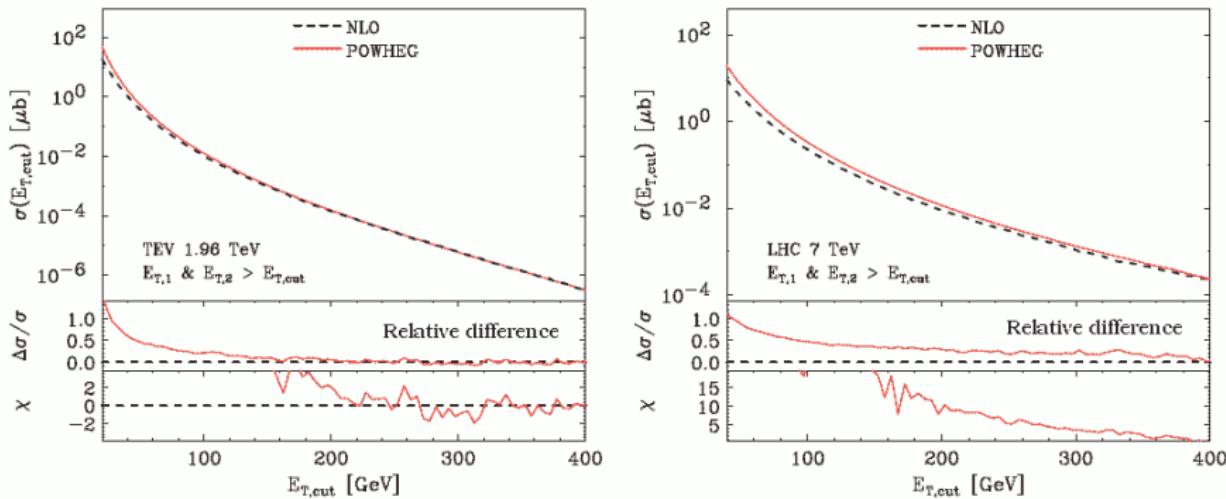


Figure 8: Predictions for the fixed-order NLO cross sections to the analogous POWHEG hardest-emission one, for symmetric cuts on the transverse energies of both the highest and second highest E_T jets, at the Tevatron and LHC, in the left- and right-hand plots respectively.

Alioli et al., arXiv:1012.3380

Practical evaluation of the combined PDF+ α_s uncertainty

Several prescriptions of varying complexity for combining the PDF and α_s uncertainties exist

In arXiv:1004.4624, we show that **addition of the α_s and PDF uncertainties in quadrature is entirely adequate in most practical situations**

Theorem

In the quadratic approximation, the total α_s +PDF uncertainty $\Delta\sigma$ for the CT10 set, for $\alpha_s(M_Z) = 0.118 \pm 0.002$, is obtained by

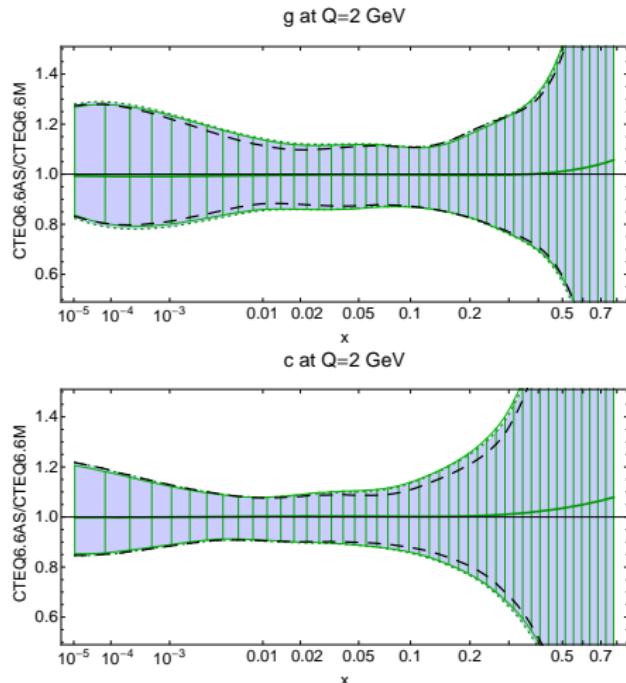
$$\Delta X = \sqrt{\Delta X_{CT10}^2 + \Delta X_{\alpha_s}^2},$$

where

- ΔX_{CT10} is the CTEQ6.6 PDF uncertainty from 44 PDFs with the same $\alpha_s(M_Z) = 0.118$
- $\Delta X_{\alpha_s} = (X_{0.120} - X_{0.116})/2$ is the α_s uncertainty computed with two central CTEQ6.6AS PDFs for $\alpha_s(M_Z) = 0.116$ and 0.120

Quadrature addition reproduces the exact PDF+ α_s uncertainty

Total PDF+ α_s errors ΔX are the **same** when found (a) from a full fit with floating α_s , or (b) by adding ΔX_{PDF} and ΔX_{α_s} in quadrature



- black – CTEQ6.6 PDF uncertainty
- Blue filled – PDF+ α_s uncertainty of the fit with floating $\alpha_s(M_Z)$
- Green hatched – PDF+ α_s uncertainty added in quadrature